Curriculum Vitae

11, Sante Tani
56123, Pisa, Italy.
+39 339 1001456
+39 050 2217316
paolo.salaris@unipi.it
Born on September, 22, 1979,
Siena, Tuscany (Italy).
Italian citizen.

Paolo Salaris

Current Position

Since September 2019 — **Assistant Professor (RTD-B)**, ***University of Pisa, Dipartimento di Ingegneria dell'informazione***, *2, Largo Lucio Lazzarino, 56126*, Pisa, Italy.

Past Positions

October 2015 – August 2019 — **Chargé de Recherche Classe Normale (CRCN), (Décision n. 2015/443/02)**, ***permanent researcher at Inria Sophia Antipolis – Méditerranée***, *Lagadic project team, 2004, route des Lucioles BP93 06902*, Sophia Antipolis (Biot), France.

February 2014 – July 2015 — **Postdoctoral researcher**, *Contract n. 451193 at LAAS–CNRS, 7, avenue du Colonel Roche, 31400*, Toulouse Cedex 4, France.
Research activity: "Motion generation and segmentation for humanoid robots". This activity was supported by the European Research Council within the project Actanthrope (ERC-ADG 340050, P.I.: Jean-Paul Laumond).

April 2013 – January 2014 — **Postdoctoral researcher**, *"Assegno di ricerca con D.R. n. 1030 del 26/01/11" at Research Center "E. Piaggio", School of Engineering, 1, Largo Lucio Lazzarino, 56122*, Pisa, Italy.
Research activity: "Study and development of optimal control and sensing strategies for autonomous grasping and manipulation with under actuated hands". This activity was supported by the European Commission under CP grant no. 248587 THE Hand Embodied, CP grant no. 600918 PacMan, and CP grant no. 287513 Saphari.

March 2011 – March 2013 — **Postdoctoral researcher**, *"Assegno di ricerca con Prot. n. 4133 del 06/03/13" at Research Center "E. Piaggio", School of Engineering, 1, Largo Lucio Lazzarino, 56122*, Pisa, Italy.
Research activity: "Study and development of models and optimal control strategies for underactuated hands". This activity was supported by the European Commission under CP grant no. 248587, THE Hand Embodied.

Education

2008–2010 — **Doctoral Degree**, *School of Engineering*, Pisa, Italy.
Ph.D. in Automatics, Robotics, and Bioengineering. Degree date: June 14, 2011

title — *From Optimal Synthesis to Optimal Visual Servoing for Autonomous Vehicles*

supervisors — Prof. Antonio Bicchi and Prof. Lucia Pallottino

1999–2007 **“Laurea” Degree**, *School of Engineering*, Pisa, Italy.
Electrical Engineering with specialization on Industrial Automation (including robotic classes).

title *Controllo di veicoli basato su retroazione puramente visiva*, (Purely image–based feedback control for vehicles)

supervisor Prof. Antonio Bicchi

Language skills

Italian Native speaker

English Intermediate (speaking, reading); advanced (writing)

French Intermediate (speaking, reading); Intermediate (writing)

Main Scientific Interests

- optimal control for robot with limited sensory systems;
- Human-aware path planning and control for robots;
- visual servoing and map building of indoor and outdoor complex and dynamics environments;
- optimal design of artificial devices;
- observability analysis, optimal estimation and active sensing control;
- optimal control of Variable Stiffness Actuators and compliant robots.

Awards

Winner of “JTCF Novel Technology Paper Award” for the paper: M. Bianchi, P. Salaris, and A. Bicchi, “Synergy-based optimal design of hand pose sensing,” in *IEEE/RSJ International Conference of Intelligent Robots and Systems*, (Vilamoura, Algarve, Portugal), October 7 – 12, 2012.

International Experiences during the PhD or Postdoc

Apr.–June 2012 **Postdoctoral Visiting Scientist**, *College de France*, Paris, France.

Research topic: “Analysis of the Optimality Principles Underlying Human Trajectories to Reach a Target”

Supervisor: Jean-Paul Laumond

During this period I worked with Jean-Paul Laumond on the optimality principles underlying human locomotion and how to transfer these principles to humanoid robots. This short period in Paris has laid the foundation for a strong and regular collaboration that allowed me to come at LAAS in Toulouse in 2014, giving also rise to a pbblication in the proceeding of ICRA 2015:

P. Salaris, C. Vassallo, P. Souères and J.-P. Laumond, “*Image-based control relying on conic curves foliation for passing through a gate*”, IEEE International Conference on Robotics and Automation (ICRA), 2015.

Mar.–Oct. 2009 **Visiting Ph.D. Student**, *University of Illinois at Beckman Institute for Advanced Science and Technology*, Urbana-Champaign, US-IL.

Research Topic: "Optimal Visual Servoing Control for nonholonomic vehicles with limited FOV monocular cameras"

Supervisor: Seth Hutchinson

During the first year of my Ph.D. I found a solution to the problem of determining the shortest path for a nonholonomic vehicle equipped with a fixed monocular camera with limited field-of-view from any initial configuration to any final one while always maintaining a given landmark in view during maneuvers. However, feedback control laws able to align the vehicle to the shortest path was still an open problem. For this reason, in the 9 months spent at Urbana-Champaign I mainly worked with Prof. Seth Hutchinson in order to determine these optimal visual feedback control laws. The outcome of this study has been published in the proceeding of IROS 2011:

P. Salaris, L. Pallottino, S. Hutchinson and A. Bicchi, "*From optimal planning to visual servoing with limited FOV*", IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 2817 - 2824, 25-30 Sept. 2011.

Current and future participation to research projects

Mobideep "Technology-aided MOBIlity by semantic DEEP learning" (ANR – Agence National de la Recherche – project starting in January 2018). The main objective of MOBI-DEEP is to develop technologies enabling (or helping) autonomous navigation of robots in open and unknown environments by means of low-cost sensors such as digital cameras and by using deep learning techniques. MOBI-DEEP will be involved in these situations through two applications: visual aid guidance for blind people and navigation for mobile robots in open areas. My role in the project will be develop re-active navigation, by exploiting semantic knowledge (characteristics of the environment and of situations of meeting, etc.), as well as geometrical and temporal knowledge (static and dynamic obstacles, collision time, time horizon, etc.). The objective is to show that the contribution of this information makes it possible to reach a given goal by only a set of re-active navigation tasks that exploit the knowledge of the state of the world built from of learning and local perception, and this without falling into a deadlock configuration.

CrowdBot "Safe Robot Navigation in Dense Crowds" (H2020 ICT-25-2017-RIA, starting in January 2018). CROWDBOT's scientific and technical objectives target step changes in robots' abilities to sense and to predict the dynamics of a crowd of pedestrians surrounding the robot so as to navigate according to the risks associated to navigating in a crowd of pedestrians. This risk assessment analysis will result in a policy for robots moving in crowds with specific dynamics, managing also contact with pedestrian if unavoidable. My role in the project will be to contribute in the development of navigation techniques to allow the robot to safety navigate through dense human crowds.

Past participation to research projects

Actanthrope "Computational Foundations of Anthropomorphic Action" (ERC-ADG 340050 of Jean-Paul Laumond, DRCE at LAAS), Start: January 2014, Duration: 60 months). Actanthrope intends to promote a neuro-robotics perspective to explore original models of anthropomorphic action. The project targets contributions to humanoid robot autonomy (for rescue and service robotics), to advanced human body simulation (for applications in ergonomics), and to a new theory of embodied intelligence (by promoting a motion-based semiotics of the human action). Within this project, I collaborated with Dr. Naoko Abe, a postdoctoral research whose focus is on dance notation and in particular on the kinetography Laban, to evaluate the pertinence of using dance notations as a method to segment complex movements also in humanoid robots. First results of this multi-disciplinary study has been published in ICKL, which is a conference in the dance notation field and then in RAM. Because of the pertinence with this ERC project, I have also proposed to Jean-Paul Laumond to carry on the work started during my visiting period at College de France as part of my personal research program: investigate the role of the visual system in human locomotion so as to transfer these fundings to humanoid robots. First results on this subject have been obtained and published in the proceeding of ICRA and TRO 2015 (see the "Research overview" part).

THE "THE Hand Embodied" (no. 248587, within the FP7-ICT-2009-4-2-1 program "Cognitive Systems and Robotics", http://www.thehandembodied.eu, Start: March 2010, Duration: 48 months). THE refers to the "hand" as both the abstract cognitive entity – standing for the sense of active touch – and the physical embodiment of such sense, comprised of actuators and sensors that ultimately realize the link between perception and action. Central to this project is the concept of constraints imposed by the embodied characteristics of the hand and its sensorimotor apparatus on the learning and control strategies we use for such fundamental cognitive functions as exploring, grasping and manipulating. Within this project I developed the synergy-based hand pose reconstruction method for low-cost sensing gloves in WP6 and results have been published in IJRR and Haptics Symposium 2012. In the contest of this project, the optimal design and reconstruction of Hand Pose Reconstruction system has been studied. Results have been published to IJRR, IROS (JTCF Novel technology paper award) and Haptics Symposium (see the "Research overview" part).

SAPHARI "Safe and Autonomous Physical Human-Aware Robot Interaction" (no. 287513, within FP7-ICT-2011-7 program "Cognitive Systems and Robotics", Start: February 2011, Duration: 48 months. http://www.saphari.eu). SAPHARI goals are to bring to fruition co-workers in real world applications using the new technologies of soft robotics that combine cognitive reaction and safe physical human-robot interaction. Moreover, it expands and improves the functionalities of robotic systems and further develop relevant features, such as autonomy, safety, robustness, efficiency, and ease of use. Within this project, in collaboration with colleagues, I was in charge of the problem "Force control laws for VIA manipulators" within WP3 "control". The objective was to provide an analysis of advantages and drawbacks of using variable impedance actuators in tasks where the force control is required. Within this context, I was in charge of writing deliverables and milestones in WP3.

Reviewer activities

Journals IEEE Transaction on Robotics; IEEE Robotics and Automation Letter; International Journal of Robotics Research; Transaction on systems, man and cybernetics (part B), IEEE Transactions on Control Systems Technology.

Conferences Program committee of Robotics: Science and Systems 2017, IEEE Conference on Robotics and Automation; IEEE/RSJ International Conference on Intelligent Robots and Systems; IEEE International Conference on Decision and Control; European control conference; American control conference.

Presentations and invited seminars

- Participation as a speaker at the IEEE/RSJ International Conference on Robot and Automation (ICRA), May, 2017, Singapore, Singapore.
- Seminar/interview for a tenure-track position in robotics at IIT in Genova, June, 2015, Genova, Italy.
- Seminar/interview for a junior researcher position (CR2 – Chargés de Recherche deuxième classe) at Inria (Institut National de Recherche en Informatique et en Automatique – French Institute for Research in Computer Science and Automation) at Inria - Sophia Antipolis Mediterranée, April, 2015, Sophia Antipolis, France.
- Seminar/interview for a junior researcher position (CR2 – Chargés de Recherche deuxième classe) at CNRS (Le Centre National de la Recherche Scientifique – French National Center for Scientific Research) in Paris, February, 2015, Paris, France.
- Participation as a speaker at the IEEE/RSJ International Conference on Robot and Automation (ICRA), May, 2015, Seattle, USA.
- Participation as a speaker to the 1st Workshop of the Anthropomorphic Motion Factory titled "Dance Notations and Robot Motion". Title of the talk: "On the use of Kinetography Laban with humanoid robots", at LAAS-CNRS, 13-14 November, 2015, Toulouse, France.
- Seminar at Rennes (Lagadic group), Nantes (Team Robotics) and Marseille (Team Biorobotics). Title of the talk: *Visual feedback control for natural motion*, France, 2014.
- Seminar within the AMARSi European project Symposium (http://www.amarsi-project.eu/): *Adaptive Motor Primitives in Brain and Machines.* Title of the Talk: *Haptic Synergies, i.e. How to Cope with Hand Sensorimotor Complexity*, University Clinic Tübingen, Germany, Medical Clinic-Lecture Hall, November 2012.
- Seminar at University of Rome "Sapienza". Title of the talk: *From optimal synthesis to optimal visual serving for autonomous vehicles*, Rome, Italy July 2011.
- Participation as a speaker at the IEEE/RSJ International Conference on Intelligent RObots and Systems (IROS), Sept., 2011, San Francisco, California (USA).
- Participation as a speaker at the IEEE/RSJ International Conference on Robot and Automation (ICRA), May, 2011, Shanghai, China.
- Participation as a speaker at the IEEE/RSJ International Conference on Intelligent RObots and Systems (IROS), Sept., 2008, Nice, France.

Teaching Experiences

The following teaching experiences concern lectures, coordinating computer-lab activities, exam tests preparation, student support and student projects tutoring for three courses, taught by Prof. Antonio Bicchi at the University of Pisa (Italy): Robotics and automatic controls (basic and advanced level). The main topics addressed in the Robotics course were: nonlinear feedback control via control-Lyapunov function of nonholonomic and holonomic vehicles with applications to path following, trajectory tracking and point-to-point stabilization (parking). Classical nonlinear control of robotics systems as e.g. computed torque, adaptive control, robust control, backstepping control, feedback linearization etc.. Observability and reachability analysis of nonlinear systems. The main topics addressed in the Automatic controls course both basic and advanced level were: analysis of mechanical systems and their dynamical model; linearization around an equilibrium position and trajectory; solution of linear continuous and discrete dynamical systems; step response; Bode, Nyquist and Nichols diagrams; stability analysis and stability margins; synthesis of the controller by using Bode diagram and/or the root locus; reachability and observability analysis of linear systems; feedforward and feedback optimal control for linear systems; poles placement by linear state feedback; Luemberger observer and regulator synthesis.

a.a. 2013/2014 **Teaching assistant**, *Course of "Robotica" (Robotics)*, Master's Degree in Robotics and Automation Engineering, Prof. Antonio Bicchi.
University of Pisa

a.a. 2013/2014 **Teaching assistant**, *Course of "Controlli Automatici" (Automatic Controls, level: Advanced)*, Master's Degree in Mechanical Engineering, Prof. Antonio Bicchi.
University of Pisa

a.a. 2012/2013 **Teaching assistant (Con contratto di collaborazione autonoma coordinata e continuativa per incarichi di supporto alla didattica, Prot. n. U/436 del 21/12/2012, 20 ore)**, *Course of "Robotica" (Robotics)*, Master's Degree in Robotics and Automation Engineering, Prof. Antonio Bicchi.
University of Pisa

a.a. 2012/2013 **Teaching assistant**, *Course of "Controlli Automatici" (Automatic Controls, level: Advanced)*, Master's Degree in Mechanical Engineering, Prof. Antonio Bicchi.
University of Pisa

a.a. 2010/2011 **Teaching assistant**, *Course of "Controlli Automatici" (Automatic Controls, level: Advanced)*, Master's Degree in Mechanical Engineering, Prof. Antonio Bicchi.
University of Pisa

a.a. 2009/2010 **Teaching assistant**, *Course of "Controlli Automatici" (Automatic Controls, level: Advanced)*, Master's Degree in Mechanical Engineering, Prof. Antonio Bicchi.
University of Pisa

a.a. 2008/2009 **Teaching assistant**, *Course of "Regolazione e controllo dei sistemi meccanici" (Automatic Controls, level: Basic)*, Bachelor's Degree in Mechanical Engineering, Prof. Antonio Bicchi.
University of Pisa

Future, current and past co-supervision of students

Andi Cristian Mindru Master Thesis "Visual Servoing of a Robotic Telescope" from September 2017 to February 2017. The goal of this thesis is to study and develop visual based control strategies in order to automatize the pointing and following of satellite through a telescope available at the Observatoire de la Côte d'Azur.

Dayana Hassan PhD thesis "Robotic platform for assistance to people with reduce mobility" (in french: "Plate-forme robotisée d'assistance aux personnes à mobilité rèduite"), starting in November 2016, ending in December 2019. In co-supervision with Dr. Patrick Rives and in collaboration with AXYN Robotics, a young startup in Robotics located near Aix en Provence which designs, manufactures and markets scalable service robots. It is currently developing a range of robots for telepresence and a platform to help the disabled people. The main objective of this PhD thesis is to develop an intelligent vehicle to help elderly or reduced mobility persons to move safely within a retirement home, an hospital or other much more crowed and dynamic environments. First of all, the vehicle has to be able to move within the environment while at the same time update the current map as accurately as possible. Once the map of the environment is available, the robot has to be able to plan the trajectory and reach a given destination. The robot should also follow a person taking into account social behaviors or bring (hence making sure that the elderly person, affected e.g. by Alzheimer's disease, follows the robot) towards a given destination, e.g. the canteen. The robot should also work as an intelligent walker and help people in case of falling. In all these cases, it is very important to include humans (i.e. his/her model, his/her behaviors, his/her intentions etc.) within the study in order to develop adaptable human-aware path planning and control strategies. AXYN Robotics will support validation methodologies developed during the thesis.

Alessio Salvatore Coppola Master Thesis "Controllo Ottimo per Veicoli Robotici da Corsa" (Optimal Control for racing robotic vehicles), 2014. With Prof. Lucia Pallottino, Research Centre "E. Piaggio", University of Pisa, Italy.

Hamal Marino, Marco Bonizzato, Riccardo Bartalucci Tutoring for the robotics class and in-depth controllability analysis of vehicles in formation, with Prof. Lucia Pallottino, Research Centre "E. Piaggio", University of Pisa, Italy. Results of this research have been published in:

H. Marino, M. Bonizzato, R. Bartalucci, P. Salaris, and L. Pallottino. "*Motion planning for two 3d-dubins vehicles with distance constraint*". In IEEE/RSJ International Conference of Intelligent RObots and Systems (IROS), pages 4702 - 4707, 2012.

Software skills

Computer programming: C/C++, python, ROS, Matlab (control system toolbox, optimization procedures, sisotool, Simulink), Mathematica.

References

Antonio Bicchi Full Professor at University of Pisa, Italy, Research Center “E. Piaggio”, 1, via Largo Lucio Lazzarino, 56126 Pisa. Phone number: +39 050 2217060, e-mail: bicchi@centropiaggio.unipi.it, web page: http://www.centropiaggio.unipi.it/%7Ebicchi

Jean-Paul Laumond Directeur de Recherche at LAAS-CNRS (Gepetto Team) in Toulouse, France, 7, avenue du Colonel Roche, 31077 Toulouse Cedex 4, Phone number: 05.61.33.63.47, e-mail: jpl@laas.fr, web page: http://projects.laas.fr/gepetto/index.php/Members/Jean-PaulLaumond

Seth Hutchinson Full Professor of Electrical and Computer Engineering at University of Illinois at Urbana-Champaign, Beckman Institute of Advanced Science and Technology, 1308 W Main Street, Urbana, Il 61801-2307, Phone number: +1 217 244-5570, e-mail: seth@uiuc.edu, web page: http://www-cvr.ai.uiuc.edu/~seth/

François Chaumette Directeur de Recherche at Inria Rennes Bretagne Atlantique - Irisa and head of the Lagadic Group, Campus de Beaulieu, 35042, Rennes cedex, France, Phone number: +33 2 99 84 72 55, e-mail: Francois.Chaumette@irisa.fr, web page: http://www.irisa.fr/lagadic/team/Francois.Chaumette-eng.html

Scientific Publications

Total citations of my publications: 260 from scopus, 395 from Google Scholar
h-index: 9 from scopus, 11 from Google scholar
(Legend: IF = Impact Factor; SJR = Scientific Journal Rankings;
SNIP: Source Normalized Impact per Paper)

Journal papers and book chapters

[1] F. A. W. Belo, **P. Salaris**, D. Fontanelli, and A. Bicchi. A complete observability analysis of the planar bearing localization and mapping for visual servoing with known camera velocities. *International Journal of Advanced Robotic Systems (IJARS)*, 10(197), April 2013. IF: 0.952; 5-Year IF: 0.659; CiteScore: 1.26; SJR: 0.364; SNIP: 0.914.

[2] M. Bianchi, **P. Salaris**, and A. Bicchi. Synergy-based hand pose sensing: Optimal glove design. *International Journal of Robotics Research (IJRR)*, 32(4):407–424, April 2013. IF: 4.047, 5-Year IF: 3.278; CiteScore: 6.06; SJR: 2.471; SNIP: 3.376.

[3] M. Bianchi, **P. Salaris**, and A. Bicchi. Synergy-based hand pose sensing: Reconstruction enhancement. *International Journal of Robotics Research (IJRR)*, 32(4):396 – 406, April 2013. IF: 4.047, 5-Year IF: 3.278; CiteScore: 6.06; SJR: 2.471; SNIP: 3.376.

[4] A. Cristofaro, **P. Salaris**, L. Pallottino, F. Giannoni, and A. Bicchi. On the minimum-time control problem for differential drive robots with bearing constraints. *Journal of Optimization Theory and Applications*, 173(3):967–993, Jun 2017. IF: 1.234; 5Year IF: 1.579; CiteScore: 1.30; SJR: 0.813; SNIP: 1.168.

[5] D. Fontanelli, A. Danesi, F. A. W. Belo, **P. Salaris**, and A. Bicchi. Visual servoing in the large. *International Journal of Robotics Research (IJRR)*, 28(6):802 – 814, June 2009. IF: 4.047, 5-Year IF: 3.278; CiteScore: 6.06; SJR: 2.471; SNIP: 3.376.

[6] D. Fontanelli, **P. Salaris**, F.A.W. Belo, and A. Bicchi. Unicycle-like robots with eye-in-hand monocular cameras: From pbvs towards ibvs. In Graziano Chesi and Koichi Hashimoto, editors, *Visual Servoing via Advanced Numerical Methods*, pages 335–360. Springer London, London, 2010.

[7] H. Marino, **P. Salaris**, and L. Pallottino. Controllability analysis of a pair of 3d dubins vehicles in formation. *Robotics and Autonomous Systems (RAS)*, 83:94 – 105, 2016. IF: 2.638, 5-Year IF: 2.809; CiteScore: 3.36; SJR: 0.711; SNIP: 1.838.

[8] **P. Salaris**, N. Abe, and J.-P. Laumond. A worked-out experience in programming humanoid robots via the kinetography laban. In Jean-Paul Laumond and Naoko Abe, editors, *Dance Notations and Robot Motion*, pages 339–359. Springer International Publishing, Cham, 2016.

[9] **P. Salaris**, N. Abe, and J. P. Laumond. Robot choreography: The use of the kinetography laban system to notate robot action and motion. *IEEE Robotics*

Automation Magazine, 24(3):30–40, Sept 2017. IF: 3.573, 5-Year IF: 5.464; CiteScore: 2.40; SJR: 0.754; SNIP: 2.087.

[10] **P. Salaris**, M. Cognetti, R. Spica, and P. Robuffo Giordano. Online optimal perception-aware trajectory generation. *IEEE Transactions on Robotics (TRO)*, pages 1–16, 2019. IF: 4.264; 5-Year IF: 3.358; CiteScore: 6.07; SJR: 1.822; SNIP: 3.147.

[11] **P. Salaris**, A. Cristofaro, and L. Pallottino. Epsilon-optimal synthesis for unicycle-like vehicles with limited field-of-view sensors. *IEEE Transactions on Robotics (TRO)*, 31(6):1404–1418, Dec 2015. IF: 4.264; 5-Year IF: 3.358; CiteScore: 6.07; SJR: 1.822; SNIP: 3.147.

[12] **P. Salaris**, A. Cristofaro, L. Pallottino, and A. Bicchi. Epsilon–optimal synthesis for vehicles with vertically bounded field-of-view. *IEEE Transaction on Automatic Control (TAC)*, 60(5):1204–1218, May 2015. IF: 5.007; 5-Year IF: 3.747; CiteScore: 5.90; SJR: 3.433; SNIP: 3.070.

[13] **P. Salaris**, D. Fontanelli, L. Pallottino, and A. Bicchi. Shortest paths for a robot with nonholonomic and field–of–view constraints. *IEEE Transaction on Robotics (TRO)*, 26(2):269 – 281, April 2010. IF: 4.264; 5-Year IF: 3.358; CiteScore: 6.07; SJR: 1.822; SNIP: 3.147.

[14] **P. Salaris**, L. Pallottino, and A. Bicchi. Shortest paths for finned, winged, legged and wheeled vehicles with side-looking sensors. *International Journal of Robotics Research (IJRR)*, 31(8):997 – 1017, May 2012. IF: 4.047, 5-Year IF: 3.278; CiteScore: 6.06; SJR: 2.471; SNIP: 3.376.

[15] **P. Salaris**, C. Vassallo, P. Sous, and J. P. Laumond. The geometry of confocal curves for passing through a door. *IEEE Transactions on Robotics (TRO)*, 31(5):1180–1193, Oct 2015. IF: 4.264; 5-Year IF: 3.358; CiteScore: 6.07; SJR: 1.822; SNIP: 3.147.

Patents

[16] M. Bianchi, **P. Salaris**, and A. Bicchi. Procedimento di ricostruzione virtuale di una posa reale di almeno una porzione di corpo umano, Sept. 2014. IT Patent n. 0001410855.

Conference proceedings

[17] F. A. W. Belo, **P. Salaris**, and A. Bicchi. 3 known landmarks are enough for solving planar bearing slam and fully reconstruct unknown inputs. In *IEEE/RSJ International Conference on Intelligent RObots and Systems (IROS)*, pages 2539 – 2545, St. Louis MO USA, October 18 – 22 2010.

[18] M. Bianchi, **P. Salaris**, and A. Bicchi. Synergy-based optimal design of hand pose sensing. In *IEEE/RSJ International Conference of Intelligent Robots and Systems (IROS)*, pages 3929–3935, Vilamoura, Algarve, Portugal, October 7 – 12 2012.

[19] M. Bianchi, **P. Salaris**, A. Turco, N. Carbonaro, and A. Bicchi. On the use of postural synergies to improve human hand pose reconstruction. In *Haptics Symposium*, pages 91–98, Vancouver, Canada, March 4 - 7 2012.

[20] M. Cognetti, **P. Salaris**, and P. Robuffo Giordano. Optimal Active Sensing with Process and Measurement Noise. In *IEEE International Conference on Robotics and Automation (ICRA)*, pages 2119–2125, Brisbane, Australia, May 2018.

[21] A. Cristofaro, **P. Salaris**, L. Pallottino, F. Giannoni, and A. Bicchi. On time-optimal trajectories for differential drive vehicles with field-of-view constraints. In *IEEE 53rd Conference on Decision and Control (CDC)*, pages 2191–2197, Dec 2014.

[22] D. Fontanelli, F. A. W. Belo, **P. Salaris**, and A. Bicchi. Visual slam for servoing for appearance based topological maps. In Springer-Verlag, editor, *Proc. Ints. Symp. Experimental Robotics (ISER)*, volume 39/2008 of *Experimental Robotics*, pages 277 – 286, 2008.

[23] M. Garabini, F. A. W. Belo, **P. Salaris**, A. Passaglia, and A. Bicchi. Optimality principles in stiffness control: The vsa kick. In *IEEE International Conference of Robotics and Automation (ICRA)*, pages 3341–3346, Saint Paul, MN, USA, May 14 – 18 2012.

[24] M. Garabini, A. Passaglia, F. A. W. Belo, **P. Salaris**, and A. Bicchi. Optimality principles in variable stiffness control: the vsa hammer. In *IEEE/RSJ International Conference on Intelligent RObots and Systems (IROS)*, pages 3770 – 3775, S. Francisco, USA, September 25 – 30 2011.

[25] G. Grioli, M. G. Catalano, M. Garabini, F. Bonomo, A. Serio, **P. Salaris**, F. A. W. Belo, M. Mancini, A. Bicchi, and A. Passaglia. Variable stiffness actuators: muscles for the next generation of robots. In *Automatica.it*, Pisa, Italy, September, 7 – 9 2011. poster presentation.

[26] H. Marino, M. Bonizzato, R. Bartalucci, **P. Salaris**, and L. Pallottino. Motion planning for two 3d-dubins vehicles with distance constraint. In *IEEE/RSJ International Conference of Intelligent RObots and Systems (IROS)*, pages 4702–4707, Vilamoura, Algarve, Portugal, October 7 – 12 2012.

[27] L. Pallottino and **P. Salaris**. On constrained optimal control problems in robotics. In *Automatica.it*, Pisa, Italy, September 7 – 9 2011.

[28] T. Rizano, D. Fontanelli, L. Palopoli, L. Pallottino, and **P. Salaris**. Global path planning for competitive robotic cars. In *IEEE 52nd Annual Conference on Decision and Control (CDC)*, pages 4510–4516, 2013.

[29] **P. Salaris**, F. A. W. Belo, D. Fontanelli, L. Greco, and A. Bicchi. Optimal paths in a constrained image plane for purely image-based parking. In *IEEE/RSJ International Conference on Intelligent RObots and Systems (IROS)*, pages 1673 – 1680, Sept. 22–26 2008.

[30] **P. Salaris**, A. Cristofaro, L. Pallottino, and A. Bicchi. Shortest paths for wheeled robots with limited field-of-view: introducing the vertical constraint. In *IEEE 52nd Annual Conference on Decision and Control (CDC)*, pages 5143 – 5149, 2013.

[31] **P. Salaris**, L. Pallottino, and A. Bicchi. Shortest paths with side sensor. In *IEEE International Conference on Robotics and Automation (ICRA)*, pages 4875 – 4882, Shangai, China, May 9 – 13 2011.

[32] **P. Salaris**, L. Pallottino, D. Fontanelli, and A. Bicchi. Shortest paths for non-holonomic vehicles with limited field of view camera. In *IEEE 48th International Conference on Decision and Control (CDC)*, pages 8434 – 8439, Shangai, China, December, 16 – 18 2009.

[33] **P. Salaris**, L. Pallottino, S. Hutchinson, and A. Bicchi. From optimal planning to visual servoing with limited fov. In *IEEE/RSJ International Conference on Intelligent RObots and Systems (IROS)*, pages 2817 – 2824, S. Francisco, USA, September 25 – 30 2011.

[34] **P. Salaris**, R. Spica, M. Cognetti, and P. Robuffo Giordano. On-line optimal perception-aware path planning for estimation enhancement. In *Automatica.it*, Milano, Italy, September 11 – 13 2017.

[35] **P. Salaris**, R. Spica, P. Robuffo Giordano, and P. Rives. Online Optimal Active Sensing Control. In *IEEE International Conference on Robotics and Automation (ICRA)*, pages 672–678, Singapore, Singapore, May 2017.

[36] **P. Salaris**, C. Vassallo, P. Sous, and J. P. Laumond. Image-based control relying on conic curves foliation for passing through a gate. In *IEEE International Conference on Robotics and Automation (ICRA)*, pages 684–690, Seattle, Washington, USA, May 2015.

[37] A. Velasco, G. M. Gasparri, M. Garabini, L. Malagia, **P. Salaris**, and A. Bicchi. Soft-actuators in cyclic motion: Analytical optimization of stiffness and pre-load. In *IEEE-RAS International Conference on Humanoid Robots (Humanoids)*, pages 354–361, Atlanta, Georgia, USA, 2013.

Research Overview

My expertise/interests have a focus on optimal control of nonlinear dynamical systems, nonlinear observability and controllability analysis, (optimal) estimation problems and sensor placements, (optimal) motion planning for robots, environment modeling, taking often inspiration from naturalistic studies on living beings and their behaviors. Results can be used to improve the scientific understanding of natural systems, and/or to enhance performance of bio-aware artificial devices. The multi-disciplinarity of my background and the wide range of fields where optimization and control methods apply form a solid basis on which I plan to build further, in connection with other disciplines.

Description of the main research topics

Nonlinear Observability analysis and active sensing control

For over twenty years, research in Simultaneous Localization and Mapping (SLAM) has been progressing. However, a rigorous disturbance observability analysis, a problem also known as Unknown Input Observability (UIO) (or as Disturbance Observability (DO)), has been lacked in the literature and only recently strong theoretical results has been obtained. In [1, 17], for the first time, an investigation on the solvability of the planar bearing SLAM problem whenever input disturbances or unknown inputs was presented. The main result of those papers was that if 3 landmark positions are known, not only the SLAM problem is solvable, as already discussed in literature, but it is also possible to completely reconstruct any kind of analytic input disturbance, even those that do not act directly on the system inputs (e.g. vehicle drift).
Currently, I am pushing forward on the problem of nonlinear observability looking for control inputs and hence trajectories that maximize the amount and quality of information regarding the world modeling and states of the robot, collected along the trajectories through the on-board sensors. This problem is also known as *Active sensing/perception control*. By solving this problem, the negative effects of the noise that corrupt sensory signals (as well as the actuation/process noise), can be reduced and hence the maximum estimation uncertainty can be reduced as well.
In humans, action selection is an important decision process that depends on the states of the body and the environment. Because signals in our sensory and motor systems are affected by variability or noise, our nervous system needs to estimate these states. Evidence from neuroscience shows that humans take into account the quality of sensory feedback when planning their future actions to better solve the aforesaid estimation problem. This seems to be achieved by coupling feedforward strategies, aimed at reducing the negative effects of noise, with feedback actions, mainly intended to accomplish a given motor task and reduce the effects of control uncertainties (by Daniel Wolpert et. al.). Robotics, on the other hand, was defined as the science that studies the intelligent connection between perception and action. Nonetheless, action and motion planning are typically aimed at determining a motion/action plan able to accomplish a given task (e.g., reaching a particular configuration) while optimizing a cost of interest (e.g., control effort), under different constraints (e.g., sensing/actuation constraints). Several methods have been proposed over the years to solve the basic problem of generating a motion plan, some of them also suitable for a real time implementation for different robotic platform as e.g., mobile (ground/flying/underwater) robots, multi-robot systems and even humanoids. However, analogously to humans, robots usually also need some level of “world modeling”, i.e., all the information (instrumental and/or strictly needed) for accomplishing a task, since on-board sensors can seldom provide all the needed information.

For instance, a robot may need to estimate its own state (e.g. pose/velocity), to self-calibrate internal parameters (e.g. mass, sensor biases, stiffness), to reconstruct the surrounding space (e.g. location of obstacles), to infer the properties of the environment it is interacting with (e.g. dynamical/geometrical properties of an object to be manipulated), or even to infer the intentions of other robots or humans. The ability of efficiently solving the "world modeling" problem obviously depends on the quality and quantity of the available sensors. However, especially when dealing with complex tasks and low-cost or limited sensing, the quality of the world modeling also strongly depends on the motions or actions chosen for performing the tasks. In particular, there may exist motions/actions that do not permit to completely solve the "world modeling" and (internal) state estimation problem [1]. At the same time, the successful generation and execution of a motion plan also depends on the accuracy of the reconstructed world state. Therefore, an interesting, and fruitful, coupling exists between perception and action: generation of a motion/action plan should find a balance between efficient task execution and improved estimation, since the quality of the latter has an impact on the possibility of correctly executing the given task.
By takin inspiration from humans, I am currently studying, from a robotics perspective, how reducing the negative consequences of noise, starting from the one coming from the sensory feedback. The goal is to improve the performances of the employed estimation algorithm in terms of precision, accuracy and convergence rate. Some preliminary results are reported in [35]. The originality of this work is to propose a method for maximizing the amount of information coming from sensory feedback, quantified by the smallest eigenvalue of the Observability Gramian, that is able to better cope with the real-time constraint of an online implementation. Moreover, to ensue well-posedness of the optimization problem, I constrained the solution to be such that the "control effort" (or energy) needed by the robot for moving along the trajectory is constant and equal to a specified value. The need of an online implementation is indeed motivated by the fact that the Gramian, and hence the acquired information along the path, is a function of the state trajectory, whose true value is not known. However, during the robot motion, it is possible to exploit a state estimation algorithm for improving online the current estimation of the true state. A converging state estimation makes it possible to continuously refine (online) the previously optimized future path by exploiting the newly acquired information during motion. To reduce the complexity of the optimization algorithm, I exploit the flatness property of the most robotic platforms and I parametrize the flat outputs by using B-Spline curves, i.e. linear combinations, through a finite number of control points, that becomes the new optimization variables, of basis polynomial functions. In [35], I test the methodology to a planar robot that needs to estimate its position by using, as its only output, the squared distance from the origin of a fixed global reference frame. Results show that along the optimized trajectory an EKF performs better, i.e. the maximum estimation uncertainty, the final estimation error and the convergence rate are smaller than along any other possible path with the same energy cost.

Can human trajectories towards a target be explained within a suitable geometric context?

Human locomotion and the optimizing principles underlying the shape of trajectories have been studied with an analytical approach by Jean Paul Laumond et. al.. The directional nature of human locomotion is shown by analyzing trajectories recorded in 7 subjects during walking tasks in an empty space toward a goal defined both in position and orientation. The main results of this study confirm that: first of all, humans tend to adopt a *nonholonomic behavior* during a rest-to-rest task if the initial configuration is far enough from the final ones. Indeed, in this case the velocity remains tangent to the sagittal plane. Second, humans select the trajectory along which the *bearing angle is minimized*. These second result enlighten the role of the visual system

in the formation of locomotor trajectories during these types of tasks. However, what is exactly the role of the visual system? or, in other words, what is the performance variable extracted from the huge amount of information coming from eyes to accomplish locomotor tasks?
To gives an answer to these questions, in [15, 36], during my stay in Toulouse and within the ERC project Actanthrope, which intends to promote a neurorobotics perspective to explore original models of anthropomorphic action, I studied the problem of steering a vehicle through a door from a geometrical point of view. The ultimate goal was to furnish some interesting, although preliminary, insights into how vision systems and the geometry of the environment may influence the shape of the paths of human beings while performing a rest-to-rest task. The peculiarity of the proposed solution is to take benefits from the geometry that naturally emerges from the problem statement. Indeed, seen from above, in the plane of the robot motion, the door is determined by two points: the feet of its vertical supports. The originality of the approach is hence to introduce coordinate systems relative to these two points. The plane around the door is hence foliated by using confocal (the feet of the door being the foci) hyperbolae and ellipses (a.k.a. elliptic coordinates system) and confocal circles that intersect at right angles (a.k.a. bipolar coordinates system). Using visual servoing we proved that these coordinates can be directly measured in the camera image plane. That is, we proved that there exists a direct link between the geometry described by hyperbolae, ellipses and circles and the projection in the image plane of the two landmarks located on the door supports and at the same height w.r.t. the plane of the robot motion. Feedback control laws based on these coordinate systems as well as proofs of asymptotic stability of the controlled system by using the Lasalle-Krasowskii principle have been provided. Moreover, as both coordinates systems are immediately available in the image plane, we basically provide Image–Based control schemes. As a consequence, neither a state observer nor other sensors, apart from a monocular camera, are necessary to execute our visual servo control scheme. Finally, a comparison between the human trajectories toward a target, e.g. a door, and the ones generated by the control laws developed in those papers has been reported. Based on these results, I believe that the solution we provided for this particular problem furnishes an interesting base for future studies on the investigation of human trajectories during a rest-to-rest task.
Currently, I am also using the Lyapunov-based Model Predictive Control to use previous Lyapunov-based control laws for the unicycle in humanoid robots. Indeed, it is well known that nonholonimc vehicle models quite well the trajectories followed by humans to reach a given target that is sufficiently far from the initial position of the robot. However, it is also well known that the model actually used to generate walking patterns in humanoid robots is basically a simple inverted pendulum. The objective is to use the Lyapunov-based model predictive control to bridge the gap between the unicycle, used to model high level tasks (as e.g. visual servoing task to walk through a door), and the inverted pendulum, used to model the low level task of generating a stable walking pattern.

From Optimal (Shortest path) Synthesis to Optimal Visual Servoing for Autonomous Vehicles

This study represents the main research activity during my PhD. The optimal control of visually guided robotic platforms has received considerable attention in the literature, mainly for robot manipulators. To date, much less is the work that has been devoted to optimal control of visually–servoed robotic vehicles. Indeed, nonoholonomic constraints of simple mobile robots (e.g. unicycle-like), and sensor systems with limited Field–of–View (FOV) (e.g. cameras), make the optimal paths planning and control very challenging.
Sensor–guided robotic locomotion in different media often takes inspiration from natural examples, e.g. from fishes, birds, and humans for underwater, aerial, or walking robots, respectively. Interestingly, several naturalistic observations show that even very different species exhibit some

similarities in their locomotion patterns: a notable one perhaps being the spiraling nature of paths that in some cases can be observed in sensory-guided tasks. As often conjectured in naturalistic studies, a common optimality principle may underpin such motion behaviors. One of the most interesting example comes from the naturalistic observation of paths followed by raptors during hunting activities (V.A. Tucker et. al.). Indeed, the most acute vision information for raptors comes from their deep foveae, which point at approximately 45^o to the right or to the left of the head axis. The deep fovea system has a limited FOV so that raptors possess no accurate front sight. This causes a conflict, for instance in falcons, which dive at prey from great distances at high speeds: at a speed of 70 m/s, turning their head sideways to view the prey with high- visual acuity may increase aerodynamic drag by a factor of two or more and slow the raptor down. It has been shown that raptors resolve this conflict by diving along a logarithmic spiral path with their head straight and one eye looking sideways at the prey, rather than following the straight path to the prey with their head turned sideways.

In [14] and [31], it has been shown, in a robotics framework, that spiraling motions appear in the solution of the problem of minimum path length and a complete synthesis of the optimal control for different robotic vehicles has been provided. In particular, we study optimal paths to a goal position for a simple model of finned, winged, and legged robotic vehicles which must keep a given feature in sight. Indeed, autonomous vehicles of different kinds often share two important characteristics with their natural counterpart, i.e. directionality of motion and limitation (and often laterality) of sensory systems (FOV). These characteristics deeply influence the accomplishment of assigned tasks, which often imply that some environment objects or landmarks are kept in sight, in order to localize itself or tracking an object. For example, many Autonomous Underwater Vehicles used in underwater surveying and navigation are designed with a preferential direction of motion (the fore) to reduce drag, and are equipped with sonar scanners to detect and recognize objects (e.g. mines, wrecks, archeological findings) on the sea bed. Three types of sonars are usually used: forward, side–looking, and squint sonars, differing for the angle between the vehicle heading and the main axis of the scanner beam. Moreover, in [13] and [32], a complete characterization of shortest paths to a goal position has been proposed for the particular case of forward sensors whose FOV is also symmetric w.r.t. the direction of motion. Application of these results to robotics can reduce the length of paths to be followed by underwater, aerial, or legged robots to reach targets in their environment. However, these works also provides some interesting, although preliminary, insights into how sensory FOV limitations may influence motion patterns in natural systems.

As a final step, in [33] an optimal feedback control scheme to drive a vehicle equipped with a limited FOV camera towards a desired position following the shortest path while keeping a given landmark in sight has been provided. Based on the particular shortest path synthesis available in [13], feedback control laws are defined for any point on the motion plane exploiting geometric properties of the synthesis itself. By using a slightly generalized stability analysis setting, which is that of stability on a manifold, a proof of stability is given.

The model adopted in previously cited papers does not take into account the upper and lower limits of the camera: indeed, the vehicle can approach and reach the feature position maintaining it in sight. To achieve the final goal of obtaining the shortest paths synthesis for the realistic case of FOVs having right, left, upper and lower limits, more recently, in [30, 12] another step toward the final goal has been done by studying the complementary case in which only upper and lower camera limits, i.e. the Vertical–FOV (V–FOV) constraints, are considered. The impracticality of paths that reach a compact set around the feature and the loss of geometrical properties of the optimal arcs (i.e. involutes of circles instead of logarithmic spirals), lead to a substantially more complex analysis for the definition of the sufficient family of optimal paths. Also in the V-FOV case, we have obtained a finite alphabet of optimal arcs but we have also shown that, from some

initial configurations of the vehicle, there exist no optimal path. However, we are always able to provide a path whose length approximates arbitrarily well any other shorter path.
Finally, in [11] the optimal synthesis obtained in [13] and in [12] are merged to obtained the final optimal synthesis in the real case of a unicycle vehicle equipped with a limited field-of-view camera with right, left, upper and lower bounds.
Recently, the minimum time control problem is also been tackled and some preliminary results on how minimum time trajectories towards a target while always keeping some landmark in view has been provided [21, 4].

Optimal control for variable stiffness actuators: performance enhancement

This work has been developed within the SAPHARI European project. The importance of Variable Stiffness Actuators (VSA) in safety and performance of robots has been extensively discussed in the last decade. It has been shown recently that a VSA brings performance advantages with respect to common actuators. In [24] and [23] the solution of the optimal control problem of maximizing the speed of a VSA at a given position is achieved. The problem takes inspiration from humans during activities such as to hammer a nail or to kick a soccer ball. The Equilibrium-Point Hypothesis (EP-H) by Feldman states that the signals the brain sends to each muscle can be interpreted as a threshold length λ of activation of that muscle. In case of agonistic and antagonistic muscles acting at the same joint, this is equivalent to set the position and the stiffness at the joint level. By shifting the lambda of both muscles in the same direction, the angular position changes while by shifting the lambda in opposite directions, the stiffness changes. In [24] and [23], a simple model of a one degree of freedom mechanical system of a VSA has been considered and the problem of determining how to optimally set the reference position and how to change the stiffness during the task in order to maximize the final link velocity at a given position has been provided. Finally, we have shown the effectiveness of our theoretical results by experimentations on a VSA whose design is such that two motor act on the same joint as agonistic and antagonistic muscles do in living beings. The optimization results (i.e. position control and stiffness at the joint level) translate in an optimal sequence of motor reference positions which might represent the robotic counterpart of λ in the EP-H.

On the use of Kinetography Laban to notate robot action and motion

Roboticists aim at segmenting robot actions into a sequence of motion primitives in order to simplify the robot programming phase. Choreographers aim at capturing the essence of human body movements within a sequence of symbols that can be understood by dancers. To that extent, roboticists and choreographers pursue the same quest. In [9], a pluridisciplinary approach combining a dance notation system (the Kinetography Laban) with a robot programming system (the Stack of Task) has been reported. Motion scores, written down by using the Laban notation, are used instead of quantitative data to compare and enlighten differences in robot and human movements. A discussion about plausible origins of these differences taking into account the implicit rules of the Kinetography Laban on how a movement is executed by humans has been done. This comparison, in the light of the Kinetography Laban, opens some challenging questions related to motion segmentation and motion naturalness. Conclusions of this work are that dance notation and robot programming pursue two different goals in two different spaces. Dance notators mainly address the physical space, while roboticists tend to bridge both physical and motor spaces. In spite of these differences of objectives, the various experiences presented contribute to open a pluridisciplinary research perspective based on a mutual understanding between robotics and movement science as addressed by choreographers and dancers. In particular the relationship between action and motion, as well as their symbolical and computational foundations, are complementary developed by dance notation practitioners and roboticists. However, the dialogue deserves to be deeper explored.

Synergy-Based Hand Pose sensing

This work has been developed within the THE European project. Hand Pose Reconstruction (HPR) systems are gaining an increasing importance, since they provide useful human-machine interfaces in many applications ranging from tele-robotics, to virtual reality, entertainment and rehabilitation. To enable a widespread use of low-cost glove-based HPR, it is crucial to address the problem of correct hand pose estimation despite the many non-idealities arising, for example, from the complexity of human hand biomechanics and from measurement inaccuracies. In [3, 19] the problem on how to optimize HPR system accuracy – for a given hardware configuration – so as to provide optimal hand pose estimation from incomplete and imperfect glove data is described. To increase the accuracy of pose reconstruction without modifying the glove hardware – hence basically at no extra cost – we propose to collect, organize, and exploit information on the probabilistic distribution of human hand poses in common tasks (*a priori* information). In other words, the main idea is to maximize their performance by exploiting knowledge on how humans most frequently use their hands. To achieve this goal, the collection, organization, and exploitation of information on the probabilistic distribution of human hand poses in common tasks has been proposed. A discussion about how a database of such a priori information can be built, represented in a hierarchy of correlation patterns or postural synergies, and fused with glove data in a consistent way has been proposed, so as to provide good hand pose reconstruction in spite of insufficient and inaccurate sensing data.
In [2, 18] the dual problem of optimal sensing glove design is addressed. The problem is to choose the optimal sensor distribution which maximizes the information about the actual hand posture. This optimal design, used with the algorithms proposed in [3], leads to a further reduction of the reconstruction error statistics. That the optimal distribution of sensitivity for HPR is not trivial is strongly suggested by observation of the human example. Indeed, several biological observations suggest that in the human hand sensory system, different typologies of proprioceptive sensors are distributed in the dorsal skin with different densities. This produces a non-uniform map of sensitivities to joint angles, whose functional motivation is unclear, but might correspond to the different importance of different elementary percepts in building an overall representation of the hand pose. In [2] we have studied the optimal design of gloves of different nature, according to a classification of current sensing technologies adopted in the domain as discrete, continuous, and hybrid. We provided, for given *a priori* information and fixed number of sensor inputs, the optimal design minimizing in average the reconstruction error (assuming that the optimal reconstruction algorithm proposed in [3] is adopted).